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Three-body Supersymmetric Top Decays

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Abstract: We discuss three-body supersymmetric top decays, in schemes both with and without R-parity conservation, assuming that sfermion masses are larger than m_t. We find that MSSM top decays into chargino/neutralino pairs have a strong kinematic suppression in the region of the supersymmetric parameter space consistent with the LEP limits, with a decay width $\leq 10^{-5}$ GeV. MSSM top decays into neutralino pairs have less kinematical suppression, but require a flavour-changing vertex, and are likely to have a smaller rate. On the other hand, R-violating decays to single charginos, neutralinos and conventional fermions can be larger for values of the R-violating couplings still permitted by other upper limits. The cascade decays of the charginos and neutralinos may lead to spectacular signals with explicit lepton-number violation, such as like-sign lepton events.

1 Introduction

Future colliders such as LHC or an e^+e^- linear collider, e.g., TESLA, will produce $\bar{t}t$ pairs with high statistics, and may be regarded as top factories. For example, the cross section for $t\bar{t}$ production at the LHC is calculated to be of the order of 800 pb [1], corresponding to the production of 1.6×10^7 or 1.6×10^8 top quarks per year in the low- and high-luminosity regimes: 10 fb^{-1} and 100 fb^{-1}, respectively. This means, in principle, that if some rare top-decay channel has a clean experimental signature without Standard Model background, one could hope to measure the branching ratio with a sensitivity of 10^{-6} or 10^{-7}. The expected top production rate at TESLA is lower by a couple of orders of magnitude, but in this case the events are much cleaner, with reduced backgrounds [2].

The study of rare decays of the top quark, the heaviest particle discovered so far, may provide an interesting probe for physics beyond the Standard Model. Indeed, novel top decays are predicted in many proposed extensions of the Standard Model [3], particularly in models of flavour physics [4]. In the minimal supersymmetric extension of the Standard Model (MSSM) with conserved R parity and light sfermions and gauginos, two-body top decays into final states containing sparticle pairs would be expected [5]. In supersymmetric models with R parity

violated, two-body decays of the top quark into a single sfermion may arise if the sfermions are light [6]. Another possibility, even in the case of heavier sfermions,is single-neutralino production in top decays [7].

The purpose of this paper is to extend previous work to a more complete study of three-body top decays. We first study chargino-neutralino production in the MSSM [8]: $t \to \chi^+ \chi b$, and then neutralino-pair production: $t \to \chi\chi c$, which could in principle also arise, particularly if there is large $\tilde{c} - \tilde{t}$ mixing. Unfortunately, we find that the present LEP constraints on the MSSM parameter space already impose strong kinematic restrictions on $\Gamma(t \to \chi^+ \chi b)$ decay, so that it is $\leq 10^{-5}$ GeV. We find that $\Gamma(t \to \chi\chi c)$ is likely to be even smaller for any amount of $\tilde{c} - \tilde{t}$ mixing. A more interesting possibility in models with R-violating supersymmetry is single chargino and neutralino production: $t \to \chi/\chi^+ \bar{q} q$. In view of the very weak bounds on R-violating t-quark couplings, we find that either of these rare top decays could be observable at LHC and TESLA, failing which the bounds on the corresponding couplings would be tightened. Finally, novel top decays to three conventional fermions are also possible in models with R-violating t-quark couplings, and might have distinctive signatures violating lepton number.

2 Top Decays to Charginos and Neutralinos in the MSSM

Two-body MSSM decays of the top quark would require the stop and/or sbottom quarks to be very light, which is disfavoured by Tevatron data, so we focus here on three-body MSSM top decays to light charginos $\chi^{\pm}$ and neutralinos χ. Even in the absence of $\tilde{c} - \tilde{t}$ mixing, tops can decay to $\chi^+ \chi$ pairs via the diagrams shown in Fig. 1. The decay width for this process depends on:

• The magnitudes of the neutralino and chargino masses and couplings, which are functions of the MSSM parameters. Assuming gaugino-mass unification, the $U(1)$ and $SU(2)$ gaugino masses M_1 and M_2 are related by $M_1 = \frac{5}{3} \tan\theta_W^2 M_2$, in which case the gaugino and higgsino masses and couplings are determined by M_2, μ and $\tan\beta$.

• The masses of the squarks $\tilde{t}$ and $\tilde{b}$. We assume these to be kinematically inaccessible to t decay, and further require that the intermediate squarks be at least 10 GeV off-shell.

We recall that the chargino and neutralino masses cannot be very light, in view of the constraints imposed by LEP and other data. Assuming gaugino-mass unification and requiring the masses to be compatible with these constraints significantly restricts the MSSM parameter space that can be of relevance. These constraints also restrict the possible couplings of squarks to charginos and neutralinos. For instance, in previous work we found that there is a significant region of the MSSM

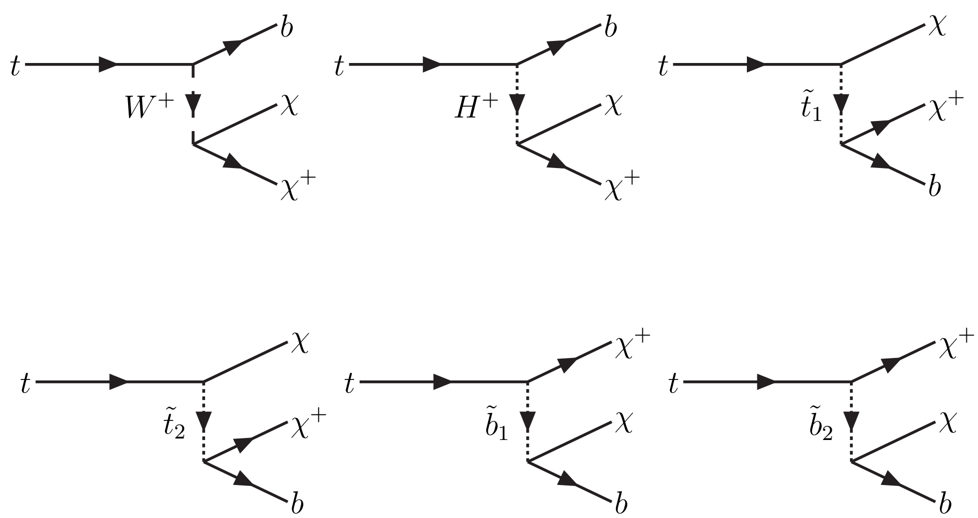

Figure 1: *Three-body top decays to charginos and neutralinos in the MSSM:* $t \to \chi^+ \chi b$.

parameter space where the couplings of the $\tilde{q}_L$ to neutralinos are strongly suppressed due to accidental cancellations [9], and the coupling of $\tilde{q}_R$ to neutralinos can be at most ≈ 0.23. On the other hand, the couplings of squarks to charginos are significantly larger, and can be as large as ≈ 0.5 in regions of the parameter space where charginos and neutralinos are relatively light.

We also note that there are regions of the MSSM parameter space where the associated production of a chargino χ^+ with the second-lightest neutralino χ' may also be kinematically possible. In this case, however, the phase-space suppression in models with gaugino-mass universality is large enough to kill any amplification that might arise due to the larger coupling of squarks to χ'. Finally, we point out that, if we postulate a deviation from gaugino-mass universality, the models most likely to yield large rates would be those where M_1 is smaller than M_2 at the input scale. In this case, the correlation between chargino and neutralino masses is broken, since the lightest neutralino is mainly a bino and the lightest chargino is mainly a wino, and thus we can allow for neutralino masses lower than the limit of about 45 GeV that is found in models with gaugino-mass universality.

Bearing these points in mind, we present in Fig. 2 contour plots for the decay width for $t \to \chi^+ \chi b$, for $\tan\beta = 5, 60$. We require $m_\chi + m_{\tilde{t}} > 185$ GeV, $m_{\chi^+} + m_{\tilde{b}} > 185$ GeV, $m_{\chi^+} > 100$ GeV and $m_\chi > 45$ GeV, in order to keep the intermediate squarks at least 10 GeV off-shell, and to be consistent with the present LEP 2 limits on chargino and neutralino masses. For illustration, we fix $m_{\tilde{q}_{L,R}} = 250$ GeV, noting, however, that mixing effects can lead to smaller physical sfermion masses, especially for large $\tan\beta$. Since we exclude the region of parameter space where the physical squark masses are small enough to allow

two-body top decays, there is a sharp cut-off in the widths for large $\tan\beta$ and relatively light $m_{\tilde{q}_{L,R}}$, visible in the second panel of Fig. 2, where we show our results for $\tan\beta = 60$.

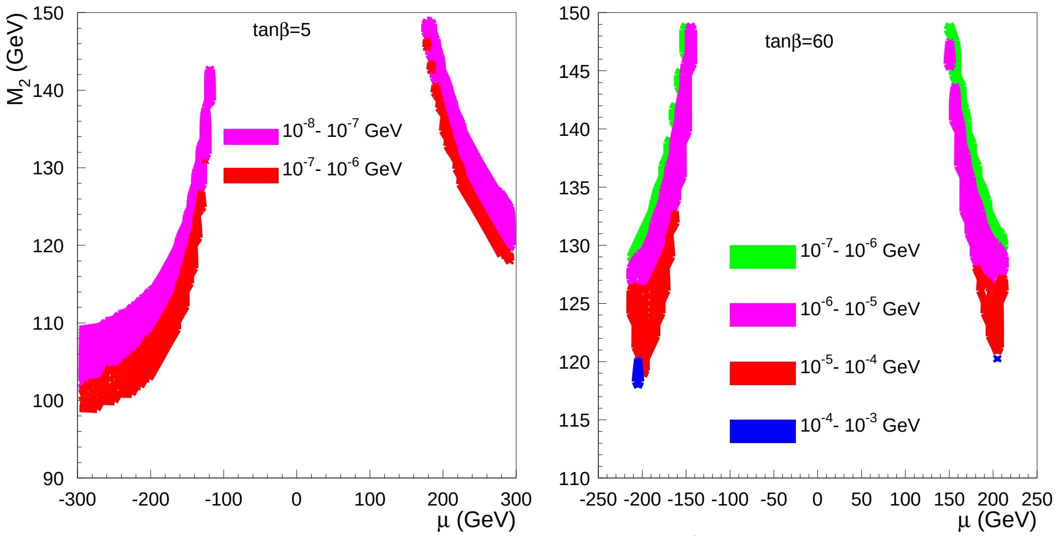

Figure 2: : *Three-body decay rates for* $t \to \chi^+ \chi b$, *for* $\tan\beta = 5, 60$, *subject to the LEP constraints. The results are plotted in the* μ, M_2 *plane, assuming gaugino-mass universality and* $m_{\tilde{q}_{L,R}} = 250$ *GeV.*

Even for large $\tan\beta$, the contribution from the Higgs-exchange diagram is at most 40-50% of the total rate. As seen in Fig. 2, generically we predict small values of $\Gamma(t \to \chi^+ \chi b)$, except for a part of the MSSM parameter parameter space with relatively small M_2 and μ, close to the LEP limits, where $10^{-6} \leq \Gamma(t \to \chi^+ \chi b) \leq 10^{-5}$ GeV. This interesting region is larger for large $\tan\beta$ because, for universal $m_{\tilde{q}_{L,R}}$, the lightest physical sbottom mass $m_{\tilde{b}_1}$ can be significantly smaller than for small $\tan\beta$. For larger values of M_2 and μ, there is a kinematical cut-off, since $m_{\chi^+} + m_\chi > m_t$, especially for larger $\tan\beta$.

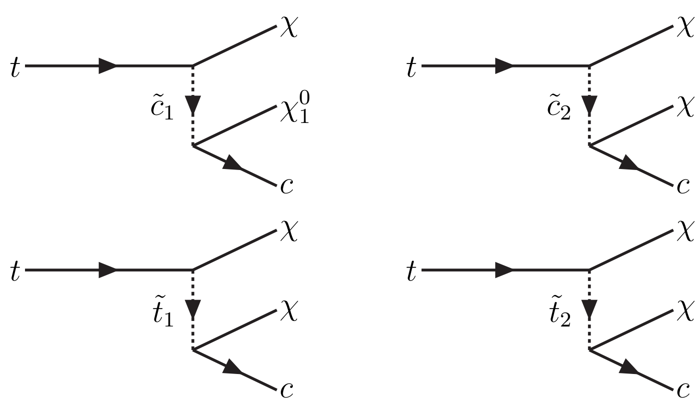

Figure 3: : *Three-body top decays pairs of neutralinos in the MSSM:* $t \to \chi\chi c$, *in the presence of* $\tilde{c} - \tilde{t}$ *mixing.*

In the case of non-negligible $\tilde{c} - \tilde{t}$ mixing, one can in principle produce via the diagrams shown in Fig. 3 a pair of neutralinos: $t \to \chi\chi c$, instead of a neutralino and a chargino: $t \to \chi^+\chi b$. However, although the phase-space suppression of the process is smaller, (i) squark-flavour mixing, and (ii) the rather small couplings of neutralinos to squarks (even for maximal mixing) in the part of the MSSM parameter space that is relevant for our calculation, both drive the expected rates to very small values. Even for large $\tilde{c} - \tilde{t}$ mixing, the expected partial decay width is typically below $10^{-7} - 10^{-8}$ GeV, and hence unobservable at either the LHC or TESLA. We therefore do not present detailed results for this decay mode.

3 R-violating Top Decays

The phenomenology of supersymmetry may not be restricted to the MSSM: the most general $SU(3)_c \times SU(2)_L \times U(1)_Y$-invariant superpotential with the field content of the minimal supersymmetric extension of the Standard Model also contains the terms

$$W = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \tag{1}$$

where L (Q) are the left-handed lepton (quark) superfields, and $\bar{E}, \bar{D}$ $(\bar{U})$ are the corresponding left-handed antilepton (antiquark) superfields. The first two operators violate lepton number, whilst the third violates baryon number. If both lepton- and baryon-number-violating operators were present at the same time in the low-energy Lagrangian, they would lead to unacceptably fast proton decay. However, it has been shown [10] that there exist symmetries which allow the violation of only a subset of these operators, leading to very rich phenomenology [11], while being consistent with the limits on proton decay.

There are 45 R-violating operators consistent with $SU(2)$ and $SU(3)$ invariance, 36 associated with lepton-number violation and 9 with baryon-number violation. Amongst all these, those operators involving a top quark can be studied directly in top decays, whereas they are currently only constrained weakly by indirect arguments. Since the $\bar{U}\bar{D}\bar{D}$ operators are likely to be 'drowned' by the QCD background, we restrict our attention to $L_i Q_3 \bar{D}_k$ and $L_i Q_j \bar{D}_3$ operators, which are bounded by several processes, as summarized in the Tables [12]. In most cases, these bounds cases simply scale with the squark masses, so we may allow for significantly larger couplings if larger sfermion masses are involved in these processes. In view of the very weak bounds on the relevant R-violating operators, either rare top decays will be observed, or certain bounds can be tightened.

In the presence of R-violating interactions, decays of the top quark into a *single sparticle* become possible, as do other potential signatures.

• If there is at least one light sfermion with $m_{\tilde{f}} < m_t$, we can expect two-body top decays $t \to \tilde{f} f'$. These have already been studied in the literature [5]. However,

ijk	λ'_{ijk}	Sources	ijk	λ'_{ijk}	Sources	ijk	λ'_{ijk}	Sources
131	0.035	A.P.P.V.	231	0.22	ν_μ D.I.S.	331	0.48	R_τ
132	0.34	R_e	232	0.36	R_μ	332	0.48	R_τ
133	0.0007	ν_e mass	233	0.36	R_μ	333	0.48	R_τ

Table 1: *Upper limits on individual $LQ\bar{D}$ operators involving the top quark [12], assuming $m_{\tilde{f}} = 100$ GeV. The allowed couplings increase as the sfermion masses become higher. We denote atomic physics parity violation by A.P.P.V., deep-inelastic scattering by D.I.S., and Z^0 decay branching ratios into $\tilde{\ell}\ell$ measured at LEP by R_ℓ.*

Combinations	Limits	Sources	Combinations	Limits	Sources
$\lambda'_{i13}\lambda'_{i31}$	8.10^{-8}	Δm_B	$\lambda'_{1k1}\lambda'_{2k2}$	8.10^{-7}	$K_L \to \mu e$
$\lambda'_{1k1}\lambda'_{2k1}$	5.10^{-8}	μTi $\to e$Ti	$\lambda_{231}\lambda_{131}$	7.10^{-7}	$\mu \to 3e$

Table 2: *Upper limits on some important products of R-violating couplings involving the top quark [12], assuming $m_{\tilde{f}} = 100$ GeV. These limits are shown for the sake of completeness: the t-decay processes we consider later are sensitive to different products of couplings.*

such a possibility is rather disfavoured, in view of the current experimental bounds and theoretical expectations, and we do not discuss this possibility further here.

• If the sfermion is a squark, one may also produce single charginos and neutralinos in three-body final states. Since there is only one massive particle in the final state, the phase space suppression is potentially less severe than in the three-body MSSM decays to chargino/neutralino pairs discussed earlier.

• There may also be decays of the top quark to three conventional fermions, via two insertions of R-violating operators.

In the remainder of this paper, we discuss the two latter options above.

• Finally, in the case of small R-violating couplings, the dominant supersymmetric decay mode of the t quark would tend to be $\chi\chi^+ b$, whilst the chargino and neutralino woul subsequently decay to fermions via the R-violating interactions. Since we predict relatively small widths for such MSSM top decays, we do not discuss this issue in detail.

3.1 Top Decay into a Single Neutralino

Top decays into a single neutralino and two conventional fermions has been discussed previously in [7], and may proceed via the diagrams shown in Fig. 4.

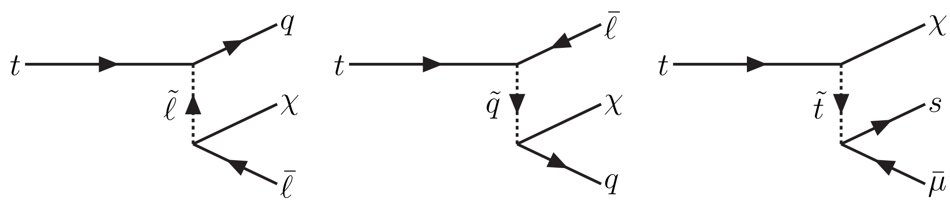

Figure 4: *Three-body t-quark decays to a single neutralino, via R-violating operators $L_i Q_3 \bar{D}_k$.*

The possible signal from this decay mode of the t quark is striking, due to the likely subsequent decay of the neutralino to an R-even final state such as $\tilde{\chi} \to q\bar{q}'\ell$ or $\tilde{\chi} \to q\bar{q}'\nu$. In particular, the subsequent decays of neutralinos can give rise to like-sign lepton signals, even if there is only one dominant R-violating operator [13]. This is because the neutralino is a Majorana spinor, and therefore can decay equally into leptons and antileptons. Any like-sign dilepton final state would be exotic, with no Standard Model physics background. Non-observation of single neutralino production in t decay at the LHC would strengthen the above bounds on R-violating couplings as a function of the other supersymmetric model parameters, as illustrated in Fig. 5, where we assume universal sfermion masses, shown as m_{squark} on the vertical axis.

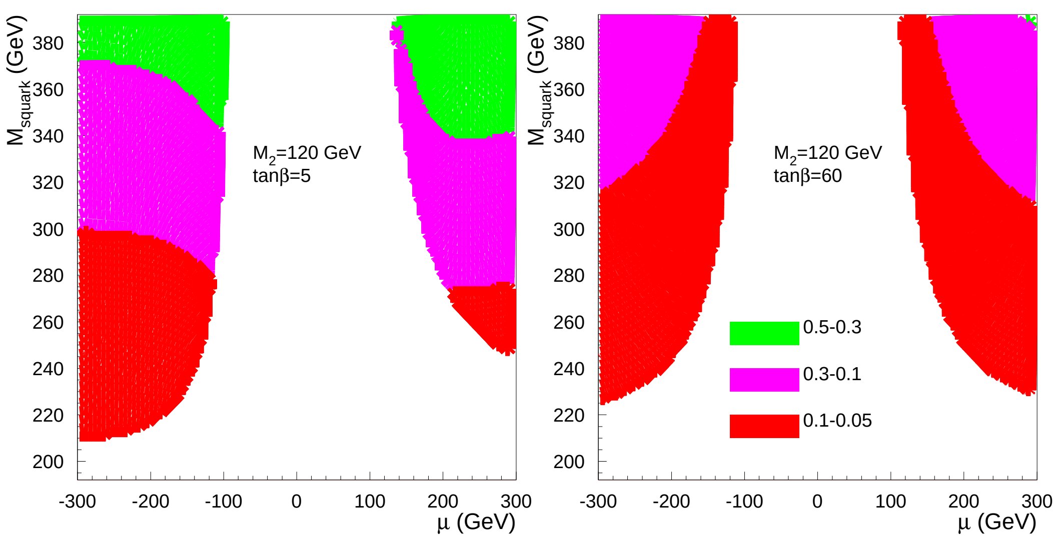

Figure 5: *Bounds on R-violating couplings available from t-quark decays to single neutralinos, for $\tan\beta = 5$, 60. The different contours denote λ' in the ranges 0.1-0.3,0.3-0.5 and 0.5-1, for a top width of 10^{-6} GeV.*

3.2 Top Decay into a Single Chargino

Top-quark decay into a single chargino and two conventional fermions may proceed via the diagrams shown in Fig. 6.

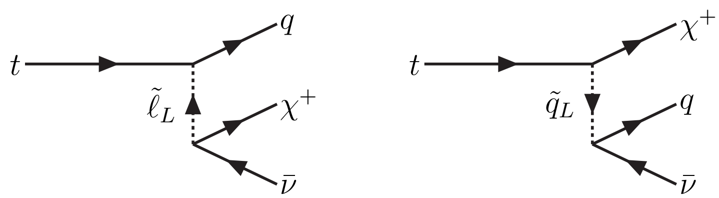

Figure 6: *Three-body t-quark decays to a single chargino, via R-violating operators $L_i Q_3 \bar{D}_k$.*

Note that we show in Fig. 6 diagrams with an electroweak-doublet field in the propagator, since if this were not the case the wino component of the chargino would be decoupled, and the chargino vertex would involve only the relatively suppressed higgsino coupling. However, even in this relatively favourable case, the decay width is suppressed by a significant factor compared to the neutralino case. This is because the chargino vertex involves a $\tilde{d}_L$ or a $\tilde{\ell}_L$ state, instead of a $\tilde{u}_L$, and thus is proportional to the U_{ij} mixing matrix element, in the notation of Gunion and Haber, rather than the V_{ij} mixing element.

We should also stress that charginos have two possible important decay modes: cascade decay via the lightest neutralino, and direct decay via R-violating coupling(s) [14]. For instance, for the lightest chargino we have the R-conserving channel $\chi^- \to \chi + (W^-)^* \to \chi + f\bar{f}'$, where $f\bar{f}'$ are the decay products of the W boson, which may be real or virtual, depending on the mass gap between the lightest chargino and neutralino, or the R-violating channels $\chi_1^- \to q\bar{q}'\ell$, $\chi^- \to q\bar{q}'\nu$, where the flavours of the quarks and the leptons depend on the flavour structure of the R-violating coupling. Which of the two processes will dominate clearly depends on (i) the strength of the R-violating operator: the stronger the operator, the larger the decay rate for direct decay of the chargino, and (ii) the difference in mass between the chargino and neutralino: if the mass gap between the two states is very small, the cascade decay is suppressed by phase space. We investigate these issues in the contour plots that appear in Fig. 7.

As seen in Fig. 7, cascade chargino decays through neutralinos, which give rise to like-sign dilepton signals, dominate over the R-violating direct chargino decay. This situation is slightly altered for smaller sfermion masses, but the R-conserving MSSM chargino to neutralino decay still dominates. The contour plots in Fig. 8 indicate that the coupling bounds from R-violating top decays to charginos are likely to be weaker than those from neutralinos. Nevertheless, the chargino decay

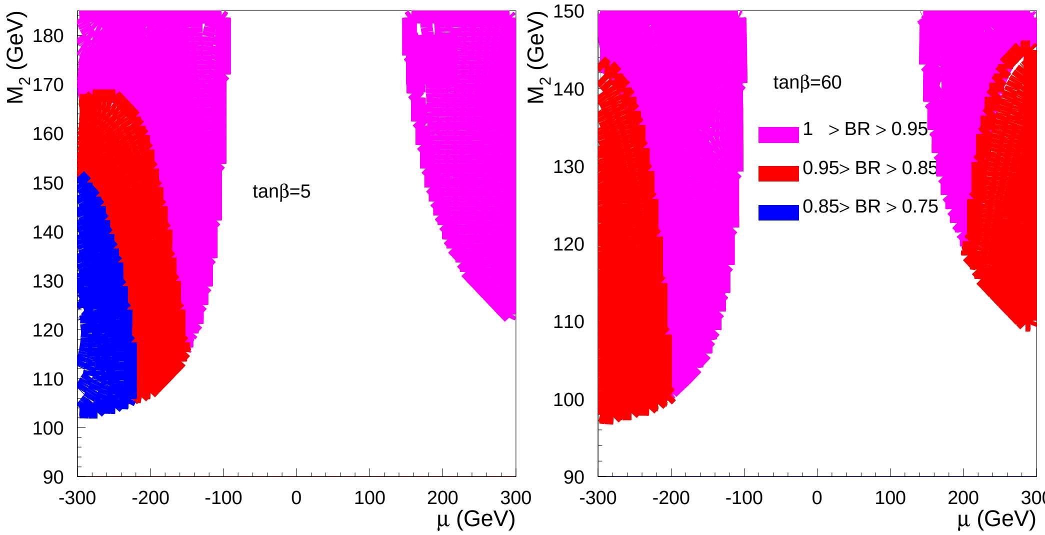

Figure 7: *Contours of the branching ratio for MSSM chargino decays, for* $\tan\beta = 5,\ 60,\ \lambda' = 0.2$ *and* $m_{\tilde{f}} = 350\ GeV$.

width is significant, and may provide a complementary channel for testing models of any R-violating top decays seen.

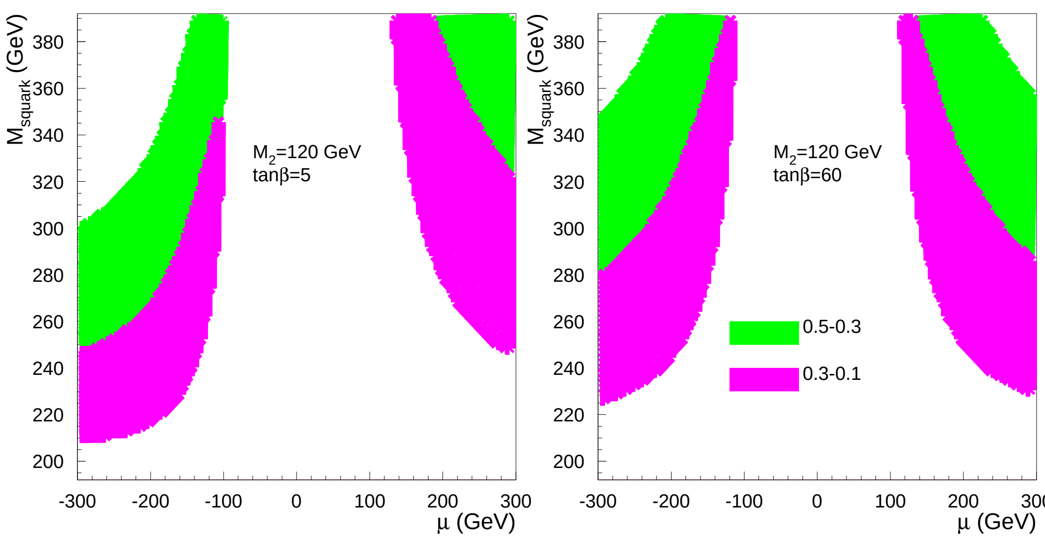

Figure 8: *Bounds on* R*-violating couplings available from* t*-quark decays to single charginos, for* $\tan\beta = 5,\ 60$*. The different contours denote* λ' *in the ranges 0.1-0.3,0.3-0.5 and 0.5-1, for a partial top decay width of* $10^{-6}\ GeV$.

3.3 Top Decays into Three Conventional Fermions

We assume that t decay occurs initially via a single dominant R-violating operator. This has to involve the top quark, and must therefore be of the type $L_iQ_3\bar{D}_k$. Then, since the $SU(2)$-singlet quark field is necessarily used in the propagator, the final states are specified to be $t \to \bar{\ell}_i\nu_i b$. This process is likely to be drowned

in the Standard Model background due to the W-exchange diagram, and therefore is lihely to be invisible, although there might be some hope in a detailed comparison of the different $t \to \bar{\ell}_i \nu_i b$ branching modes.

The situation changes when two R-violating operators are simultaneously large. The first should be of the type $L_i Q_3 \bar{D}_k$, whilst the second should be of the type $L_s Q_q \bar{D}_r$, where $r = k$ [1]. Since the $SU(2)$-singlet squark in the propagator can lead to either an up-type quark and a charged lepton or a down-type quark and a neutrino (where $q \neq 3$ for the second operator), in 50% of the cases we observe top decay to a quark and two charged leptons, via the second diagram of Fig. 9. On the other hand, for $q = 3$ the final state is necessarily $t \to \bar{\ell}_i \nu_i b$, which we consider to be indistinguishable from the Standard Model background.

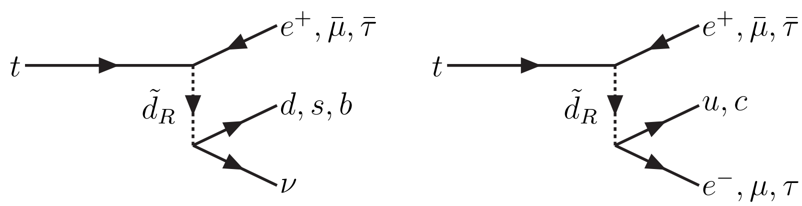

Figure 9: *Three-body t-quark decays to conventional fermions, via the R-violating operators $L_i Q_3 \bar{D}_1$ and $L_j Q_2 \bar{D}_1$.*

We find that, for $\lambda'_{ijk}\lambda'_{spk} \geq 0.09$ and squark masses of 200 GeV, the width for this three-body decay is $\mathcal{O}(10^{-5})$ GeV. Given that, for certain flavours, the current bound on $\lambda'_{ijk}\lambda'_{spk}$ for sfermions of mass 200 GeV can be as large as unity, R-violating top decays to three conventional fermions are promising. The absence of a signal could again be translated to a bound on the respective products of R-violating couplings, as seen in Fig. 10.

4 Conclusions

We have studied three-body supersymmetric top decays to charginos, neutralinos and fermions, both in the MSSM and in schemes with R-violation. Whilst the MSSM top decay widths are typically below 10^{-5} GeV, the R-violating decays to single charginos, single neutralinos, and all-fermion final states can be larger, for values of the coupling constants of R-violating interactions consistent with the present experimental upper limits.

[1] There might also be combinations of $L_i Q_3 \bar{D}_k$ and $LL\bar{E}$ operators. However, in view of the very strong bounds on $LL\bar{E}$ couplings [12], we do not consider this possibility further.

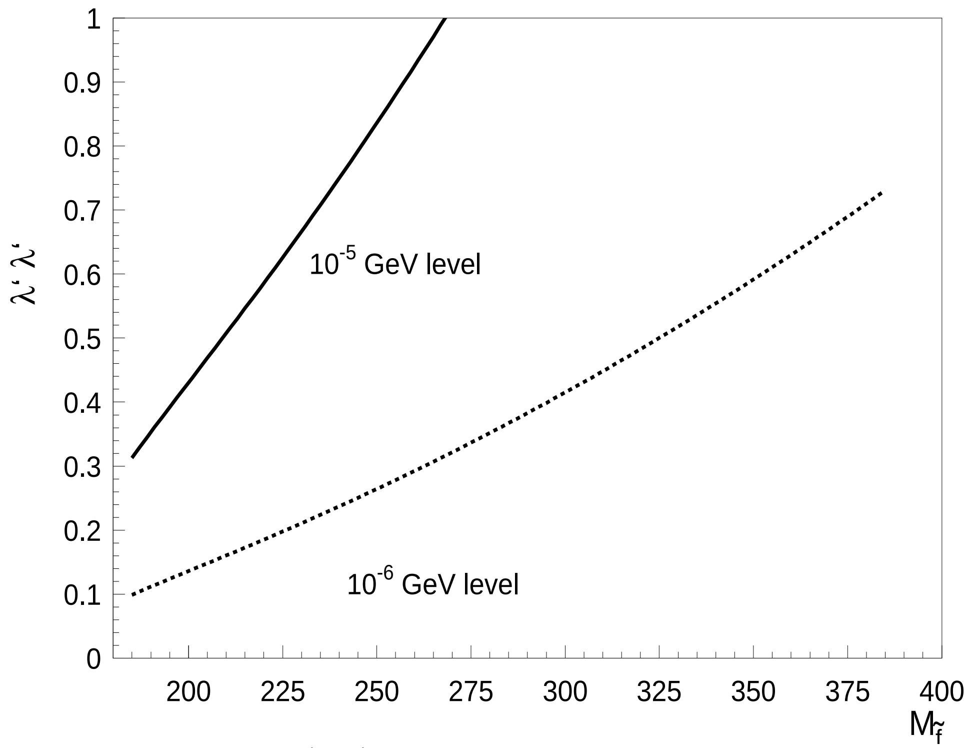

Figure 10: *Bounds on $\lambda'_{i3k}\lambda'_{spk}$ as a function of $m_{\tilde{f}}$ for a partial decay width discovered at the level of 10^{-5} or 10^{-6} GeV.*

The cascade decays of the charginos and neutralinos would lead to signals with like-sign lepton events, whilst the top decays to three fermions including two charged leptons are also signatures that may be of interest. Moreover, the decay widths of the processes studied are highly correlated and very sensitive to the supersymmetric model parameters. This means that, if such signals are observed, the allowed ranges of these parameters will be severely constrained. In the absence of signals, new bounds on single or products of R-violating couplings may be derived.

We conclude that three-body supersymmetric top decays may provide a fertile testing-ground for probing supersymmetric extensions of the Standard Model, particularly extensions of the MSSM to include R-violating couplings.

Acknowledgements

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